1 Introduction

1.1 Overview

The Hydrogen and Fuel Cell Technologies Office (HFTO) in the U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE) leads federal research, development, and demonstration (RD&D) activities to enable the commercial viability of hydrogen and fuel cell technologies.

The ***Multi-Year Program Plan*** **(*MYPP*)** sets forth HFTO's mission, goals, and strategic approach relative to DOE's broader clean energy priorities. It identifies the challenges that must be overcome to realize the full potential of clean hydrogen and fuel cells and explains how HFTO's activities will help overcome those challenges. The *MYPP* details how each subprogram within HFTO supports the office's overall strategic and performance goals, and it serves as an operational guide to help HFTO manage and coordinate activities, as well as a resource to help communicate its mission and goals to stakeholders and the public.

The *MYPP* reflects the key role HFTO plays in DOE's overarching Hydrogen Program. In addition to coordinating activities across multiple offices in the Hydrogen Program over the past two decades, HFTO also leads RD&D efforts in the production of hydrogen from renewable resources and in the storage, delivery, and utilization of clean hydrogen from diverse domestic resources. The *MYPP* lays out the detailed RD&D strategies for HFTO and is consistent with the overarching *DOE Hydrogen Program Plan*[9] as well as legislative requirements (see Chapter 1.4 for further discussion of the DOE Hydrogen Program). The *MYPP* synthesizes details from previous plans and provides context for HFTO's activities in hydrogen and fuel cells for Fiscal Year 2024 and the next several years.

This document provides a plan for the HFTO RD&D portfolio, specifically addressing objectives and targets for clean hydrogen and fuel cell technologies, which align closely with national clean energy priorities.

[9] U.S. Department of Energy. *Department of Energy Hydrogen Program Plan*. November 2020. DOE/EE-2128. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/hydrogen-program-plan-2020.pdf.

1.2 Role and Benefits of Clean Hydrogen

Clean hydrogen is a key part of a comprehensive portfolio of technologies and fuels needed to achieve our nation's climate goals and build a sustainable, secure, and equitable clean energy economy. Clean hydrogen, which has very low or zero emissions, can be produced in every part of the country and from virtually any energy resource (such as renewables, nuclear, or fossil energy with carbon capture). Hydrogen is the most abundant element in the universe; however, it is rarely found in its elemental form on Earth. It must be extracted from a hydrogen-containing feedstock (e.g., water, biomass, fossil fuels, or waste materials) using an energy source (e.g., renewables, nuclear, or fossil energy). Most of the hydrogen used today is produced from natural gas (without carbon capture, utilization, and storage [CCUS]) through a process known as steam methane reforming, resulting in substantial carbon emissions. However, there are many possible pathways for producing clean hydrogen with very low or zero emissions—for example, using renewable or nuclear power to split water, or through steam methane reforming with carbon capture.

Once hydrogen is produced, it can be used to store, move, and deliver low- or no-carbon energy to where it is needed. Hydrogen can be stored as a liquid or gas, or stored within a chemical compound, and it can release stored energy through highly efficient electrochemical processes in fuel cells, or via traditional combustion methods in engines, furnaces, or gas turbines. It can also be used as a critical feedstock and reactant in important chemical and industrial processes.

Clean hydrogen has a particularly important role to play in addressing our hardest-to-decarbonize sectors, which include key economic engines that are essential to the modern American economy and quality of life, such as heavy-duty transportation and chemical and industrial processes like ammonia production (e.g., for fertilizer), steelmaking, and production of liquid fuels (including low-emissions biofuels, which will play an important role in decarbonizing the transportation sector).[10] Clean hydrogen can also support the expansion of zero-emissions electricity by providing a means for long-duration energy storage and by offering flexibility and multiple revenue streams for all types of clean power generation.

The *U.S. National Clean Hydrogen Strategy and Roadmap*[11] estimates that by 2050, the use of clean hydrogen across sectors can reduce U.S. greenhouse gas (GHG) emissions approximately 10% relative to 2005,[12] or roughly 650 million metric tons per year—a reduction greater than the

[10] U.S. Department of Energy. *The U.S. National Blueprint for Transportation Decarbonization.* January 2023. DOE/EE-267. https://www.energy.gov/eere/us-national-blueprint-transportation-decarbonization-joint-strategy-transform-transportation.

[11] U.S. Department of Energy. *U.S. National Clean Hydrogen Strategy and Roadmap*. 2023. https://www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap.

[12] Emission savings estimated in the *U.S. National Clean Hydrogen Strategy and Roadmap* are based on ranges of hydrogen production carbon intensities, accounting for hydrogen fossil and clean electrolysis pathways, as well as hydrogen demands across transportation, industry, and grid energy storages. Estimates were developed using Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy Use in Technologies (GREET) Model: https://greet.es.anl.gov/.

annual GHG emissions from every truck, bus, airplane, and ship in the United States today.[13] By enabling diverse, domestic clean energy pathways across multiple sectors of the economy, clean hydrogen will also strengthen American energy independence and resilience while creating good jobs, economic growth, and export opportunities. The DOE report *Pathways to Commercial Liftoff: Clean Hydrogen*[14] estimates that by 2030, the hydrogen economy could also result in 100,000 net new direct and indirect jobs in the United States due to the build-out of new capital projects and clean hydrogen infrastructure.

As shown in Figure 1.1, which illustrates the H2@Scale™ vision launched in 2016 by DOE and its national laboratories, clean hydrogen can be produced from diverse domestic resources and used across almost all sectors of the economy.[15] Hydrogen production can be centralized or decentralized, grid-connected or off-grid—offering scalability, versatility, and resiliency. Clean hydrogen provides multiple options across sectors and can complement today's conventional grid and natural gas infrastructure. Because hydrogen can be stored, transported, and used in locations or applications where electrification may be challenging, it can play an especially valuable role in complementing "electrons to electrons" pathways such as the electric grid to batteries.

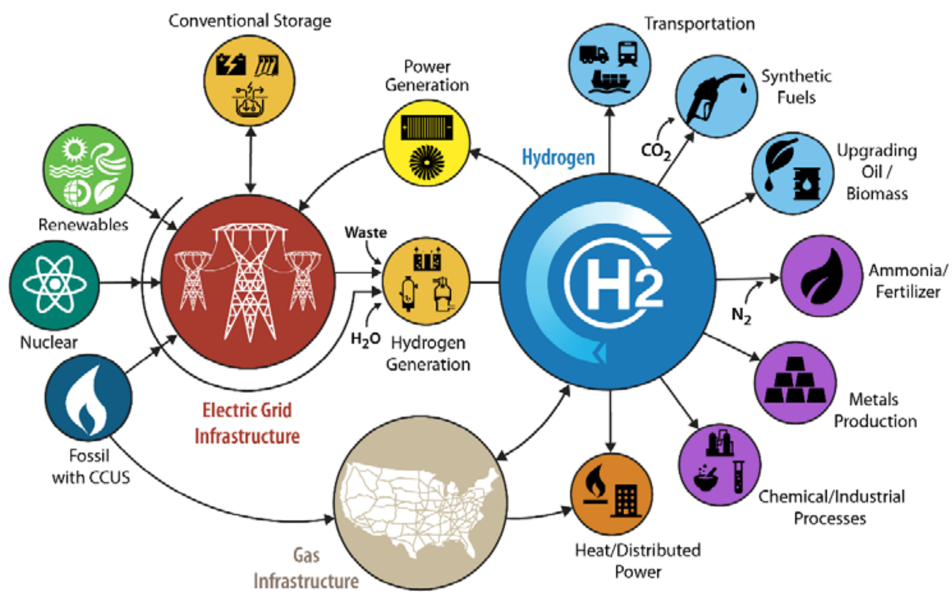

Figure 1.1. DOE's H2@Scale initiative seeks to enable resource integration and decarbonization across sectors using clean hydrogen, which can be produced from several domestic resources and used in a wide range of applications.

[13] U.S. Environmental Protection Agency. *Fast Facts: U.S. Transportation Sector Greenhouse Gas Emissions, 1990-2021.* June 2023. EPA-420-F-23-016. https://www.epa.gov/system/files/documents/2023-06/420f23016.pdf.
[14] U.S. Department of Energy. *Pathways to Commercial Liftoff: Clean Hydrogen.* March 2023. https://liftoff.energy.gov/wp-https://liftoff.energy.gov/wp-content/uploads/2023/05/20230320-Liftoff-Clean-H2-vPUB-0329-update.pdf.
[15] U.S. Department of Energy. "H2@Scale." https://www.energy.gov/eere/fuelcells/h2scale.

Figure 1.2 illustrates the wide range of specific applications where the use of hydrogen is either growing or has the potential for significant future demand. These diverse applications highlight the scale of the commercial potential for hydrogen and related technologies, as well as their decarbonization potential.

	Industrial feedstocks	Transportation	Power generation & energy storage	Buildings and hydrogen blending
Existing demands at limited current scales	• Oil refining • Ammonia • Methanol • Other (e.g. food, chemicals)	• Forklifts and other material-handling equipment • Buses • Light-duty vehicles	• Distributed generation: primary and backup power • Renewable grid integration with storage and other ancillary services	• Low-percentage hydrogen blending in limited regions
Emerging demands and potential new opportunities	• Steel and cement manufacturing • Industrial heat • Bio/synthetic fuels and products using hydrogen	• Hydrogen / biofuels using hydrogen for medium- and heavy-duty applications: o Trucks o Rail o Maritime o Aviation (e.g., sustainable aviation fuels) o Off-road equipment (mining, construction, agriculture)	• Long-duration energy storage • Hydrogen low NOx combustion • Direct/reversible fuel cells • Nuclear/hydrogen hybrids • Fossil/waste/biomass hydrogen hybrids with CCUS	• Mid- to high-percentage hydrogen blending in certain regions with limited alternatives • Building or district heating, including fuel cells and combined heat and power, for hard-to-electrify or limited options

Figure 1.2. Existing and emerging demands for hydrogen

Approximately 10 million metric tons (MMT) of hydrogen are currently produced in the United States each year, with about 100 MMT produced globally,[16] mostly from natural gas using conventional reforming processes that emit CO_2 at rates of around 10 kg of CO_2 per 1 kg of hydrogen produced.[17] This hydrogen is primarily used for oil refining and ammonia and methanol production. Replacing this unabated fossil-based hydrogen with *clean* hydrogen in these current uses offers significant near-term decarbonization potential. And using clean hydrogen in new applications like sustainable aviation fuels, steel manufacturing, and long-duration energy storage provides substantial additional decarbonization opportunities across many industries.

The *U.S. National Clean Hydrogen Strategy and Roadmap* identifies opportunities for increasing clean hydrogen production in the United States from a small fraction of current hydrogen production to ***10 MMT per year by 2030, 20 MMT per year by 2040, and 50 MMT per year by 2050*** (Figure 1.3). These goals are based on demand scenarios assuming cost competitiveness for

[16] International Energy Agency. "Global Hydrogen Review 2022." International Energy Agency, Paris, France, 2022. iea.blob.core.windows.net/assets/c5bc75b1-9e4d-460d-9056-6e8e626a11c4/GlobalHydrogenReview2022.pdf.
[17] National Energy Technology Laboratory. *Hydrogen Shot Technology Assessment: Thermal Conversion Approaches*. December 2023. https://netl.doe.gov/projects/files/HydrogenShotTechnologyAssessmentThermalConversionApproaches_120523.pdf

hydrogen use in specific sectors. The *U.S. National Clean Hydrogen Strategy and Roadmap* estimates that by 2050, the use of clean hydrogen across sectors can reduce U.S. GHG emissions approximately 10% relative to 2005.[18]

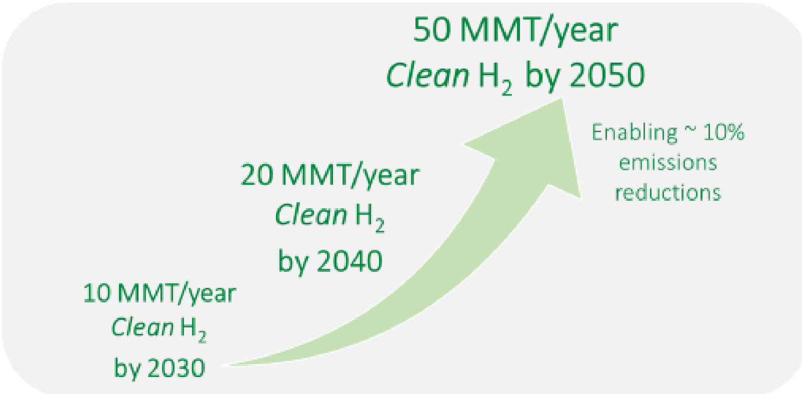

Figure 1.3. The opportunity for clean hydrogen in the United States

1.3 Challenges to Realizing Widespread Adoption of Hydrogen and Fuel Cells

Extensive technical progress has been achieved through decades of strategic investments in research, development, demonstration, and deployment (RDD&D). And this progress has laid the groundwork for rapid worldwide growth in industry investments, expanding commitments by governments and industry stakeholders to ramp up clean hydrogen production, and for the development of government and industry roadmaps for clean hydrogen across the world.[19] However, some significant challenges still need to be overcome to fully realize the enormous potential of a clean hydrogen economy. These challenges cut across the hydrogen value chain, from how hydrogen is produced, delivered, and stored to how it is used in various applications and integrated into larger energy systems. The primary challenges can be grouped into the following three categories:

- **Reducing cost and improving performance.** The cost of technologies for producing, delivering, and storing clean hydrogen, as well as the cost of fuel cells, must be reduced to expand existing markets and open new ones. The efficiency, durability, and reliability of hydrogen and fuel cell systems also need to be improved to achieve parity with incumbent technologies.
- **De-risking and scaling up technologies across the value chain.** To reduce investment risk, new hydrogen and fuel cell technologies need to be demonstrated and validated in

[18] U.S. Environmental Protection Agency. *Fast Facts: U.S. Transportation Sector Greenhouse Gas Emissions, 1990-2021.* June 2023. EPA-420-F-23-016. https://www.epa.gov/system/files/documents/2023-06/420f23016.pdf.
[19] Examples include the Hydrogen Council's *Hydrogen Scaling Up: A Sustainable Pathway for the Global Energy Transition*, 2017. https://hydrogencouncil.com/wp-content/uploads/2017/11/Hydrogen-Scaling-up_Hydrogen-Council_2017.compressed.pdf.

real-world conditions. And to enable scale-up of proven technologies, more-robust domestic supply chains and improvements in manufacturing (both to reduce cost and enable scale) will be needed.

- **Barriers to large-scale adoption.** To enable large-scale adoption across multiple sectors, improvements will be needed in a number of crosscutting areas, such as safety (e.g., improved sensors, enhanced safety practices, and knowledge dissemination), adoption of technically sound codes and standards, improved (and streamlined) permitting processes, and a well-trained workforce for the entire technology life cycle, from research through manufacturing to installation, repair, and decommissioning.

1.4 Alignment with National Priorities and Other Federal Activities

HFTO's strategy and plans are closely aligned with the overarching national clean hydrogen strategy as well as with priorities and activities within DOE and across multiple federal agencies. As laid out in the *U.S. National Clean Hydrogen Strategy and Roadmap*, the federal government is undertaking a holistic, whole-of-government approach to overcoming the challenges facing clean hydrogen. The Hydrogen Interagency Task Force[20] (HIT) coordinates activities across multiple agencies, including long-standing efforts within DOE's Hydrogen Program,[21] as guided by the *DOE Hydrogen Program Plan*.

U.S. National Clean Hydrogen Strategy and Roadmap Vision

Affordable clean hydrogen for a net-zero-carbon future and a sustainable, resilient, and equitable economy

The *U.S. National Clean Hydrogen Strategy and Roadmap*—which was required by the Infrastructure Investment and Jobs Act, also known as the Bipartisan Infrastructure Law[22]—was published in June 2023 and provides a living strategy to enable the vision for clean hydrogen. It examines the status of the hydrogen industry and the challenges facing clean hydrogen production, transport, storage, and use in the United States today. And it provides an assessment of the opportunity for hydrogen to contribute to national decarbonization goals across sectors over the next 30 years. Both the *U.S. National Clean Hydrogen Strategy and Roadmap* and the *MYPP* are guided by input from diverse stakeholders engaged in relevant private and public sector hydrogen activities. The national vision for clean hydrogen, along with key strategic priorities, are illustrated in Figure 1.4, and the three key strategies are described below.

---

[20] U.S. Department of Energy. "Hydrogen Interagency Task Force." https://www.hydrogen.energy.gov/interagency.
[21] U.S. Department of Energy. "Hydrogen Program." https://www.hydrogen.energy.gov/.
[22] Infrastructure Investment and Jobs Act. Public Law 117–58. 2021. Section 40314, (42 U.S.C. 16161c). https://www.congress.gov/117/plaws/publ58/PLAW-117publ58.pdf.

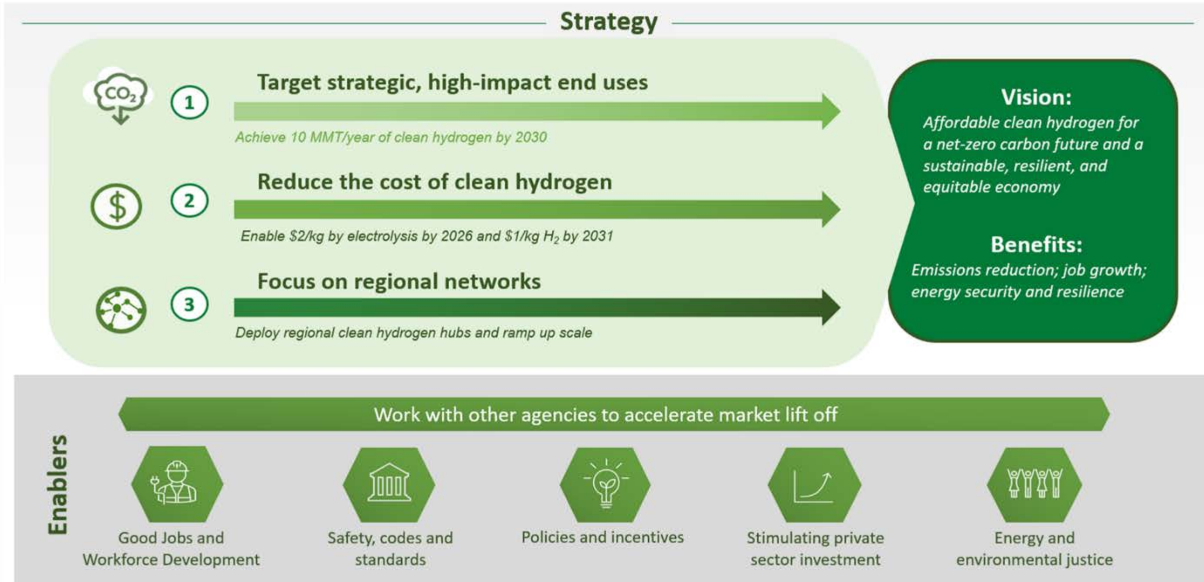

Figure 1.4. The national strategy for clean hydrogen is aligned with DOE and HFTO missions.

1. **Target strategic, high-impact end uses**: The use of clean hydrogen will be focused strategically to provide maximum benefits, particularly in sectors that are hard to decarbonize.
2. **Reduce the cost of clean hydrogen**: The United States can dramatically lower the delivered cost of clean hydrogen by developing sustainable and supply-resilient pathways including water electrolysis; thermal conversion with CCUS; and advanced or hybrid production pathways.
3. **Focus on regional networks**: Scale can be achieved strategically by focusing on regional networks—ramping up hydrogen production and end-use in close proximity to drive down transport and infrastructure costs and create holistic ecosystems that provide local benefits.

Launched in August 2023, the HIT is a collaboration among U.S. federal agencies to further advance a whole-of-government approach to executing the national clean hydrogen strategy, including development of a robust market supported by domestic supply chains and sustainable jobs. HIT members work to coordinate federal adoption of hydrogen and fuel cell technologies to support national commercialization and industry growth. Activities are conducted under staff-level working groups, which include Supply and Demand at Scale; Infrastructure, Siting, and Permitting; and Analysis and Global Competitiveness, along with other crosscutting teams. Interagency coordination will continue to expand to implement the national strategy, and agencies may be added to the HIT as the clean hydrogen economy develops over time.

As the coordinating office of the DOE Hydrogen Program, HFTO works closely with other DOE offices (e.g., Fossil Energy and Carbon Management, Nuclear Energy, Electricity, Science, Loan Programs, Manufacturing and Energy Supply Chains, Clean Energy Demonstrations, Energy

Justice and Equity, and the Advanced Research Projects Agency-Energy) and provides leadership in coordinating activities with other federal agencies, state agencies, regional partnerships, associations, and international counterparts worldwide. HFTO's plans and those of all other DOE offices are conducted under the overarching guidance of the *DOE Hydrogen Program Plan***,** which was updated in 2020 and presents an agency-wide strategic plan for all DOE offices engaged in hydrogen-related activities.

HFTO's activities in clean hydrogen production are also coordinated under the Hydrogen Shot,[23] the first of DOE's Energy Earthshots™, which was launched in June 2021 with an ambitious goal to reduce the cost to producing clean hydrogen by 80% to $1 per 1 kilogram in 1 decade ("1 1 1"). The Energy Earthshots initiative aims to accelerate breakthroughs of more abundant, affordable, and reliable clean energy solutions.

The *MYPP* also aligns with other important strategy documents such as DOE's *Pathways to Commercial Liftoff: Clean Hydrogen* and *Industrial Decarbonization Roadmap*,[24] as well as the *U.S. National Blueprint for Transportation Decarbonization*,[25] which was jointly issued by DOE, the U.S. Department of Transportation, the U.S. Environmental Protection Agency, and the U.S. Department of Housing and Urban Development. The *MYPP* also addresses fundamental research priorities, such as those identified in the DOE report *Foundational Science for Carbon-Neutral Hydrogen Technologies*.[26]

Figure 1.5. Important strategic documents underlying the HFTO RD&D strategy

[23] Office of Energy Efficiency and Renewable Energy. "Hydrogen Shot." https://www.energy.gov/eere/fuelcells/hydrogen-shot.
[24] U.S. Department of Energy. *Industrial Decarbonization Roadmap*. September 2022. https://www.energy.gov/industrial-technologies/doe-industrial-decarbonization-roadmap.
[25] U.S. Department of Energy. *The U.S. National Blueprint for Transportation Decarbonization.* January 2023. DOE/EE-267. https://www.energy.gov/eere/us-national-blueprint-transportation-decarbonization-joint-strategy-transform-transportation.
[26] U.S. Department of Energy. *Foundational Science for Carbon Neutral Hydrogen Technologies*. October 2021. https://www.energy.gov/policy/articles/foundational-science-carbon-neutral-hydrogen-technologies.

1.5 HFTO RD&D Framework

The HFTO Mission

RD&D to enable affordable clean hydrogen and fuel cell technologies for a sustainable, resilient, and equitable net-zero emissions economy.

HFTO's mission is to enable affordable clean hydrogen and fuel cell technologies for a sustainable, resilient, and equitable net-zero emissions economy. HFTO strategically deploys funding for RD&D activities to achieve the goals that support this mission. HFTO-funded efforts fall roughly into two broad areas:

- **Research and development** activities, which aim to improve materials, components, and subsystems at laboratory scale. These activities address many of the underlying technical barriers to reducing the cost and improving the performance of key technologies, such as electrolyzers, fuel cells, and systems for storing, delivering, and dispensing hydrogen. Many of HFTO's research and development efforts are conducted through consortia based on teams built around national laboratories, such as the HydroGEN Advanced Water Splitting Materials Consortium, which focuses on materials to improve hydrogen production through advanced water-splitting processes; the Hydrogen Materials Advanced Research Consortium (HyMARC), which aims to address scientific challenges in the development of viable solid-state materials for storage of hydrogen on board vehicles; and the Million Mile Fuel Cell Truck Consortium, which focuses on improving the durability, performance, and cost of fuel cells for heavy-duty trucks.
- **Demonstration and enabling** activities, which involve integration and operation of complete systems under real-world conditions to validate performance and de-risk investment, along with activities to support the deployment of commercial-scale systems and identify and help overcome nontechnological barriers. Activities focus on key strategic applications, such as demonstrations of fuel-cell-powered delivery trucks, fueling infrastructure for medium- and heavy-duty trucks, airport ground support equipment, and nuclear-to-hydrogen production. Additional enabling activities include comprehensive analysis, tools, and models to identify barriers and pathways to success; safety research; support for development of codes and standards; workforce development activities; and support for supply chains and improved manufacturing processes.

As the guiding document for HFTO's activities, the *MYPP* provides an assessment of the challenges that still must be overcome to realize large-scale adoption of clean hydrogen and a detailed, integrated plan for all RD&D and crosscutting activities conducted by HFTO. For each technical area within HFTO, the *MYPP* includes the following:

- Assessment of the current status of key metrics (e.g., electrolyzer capital cost and efficiency).

- Technical targets related to each of those key metrics (See Chapter 1.6 for a deeper discussion of HFTO's technical targets).
- Detailed plan for activities to meet those targets.

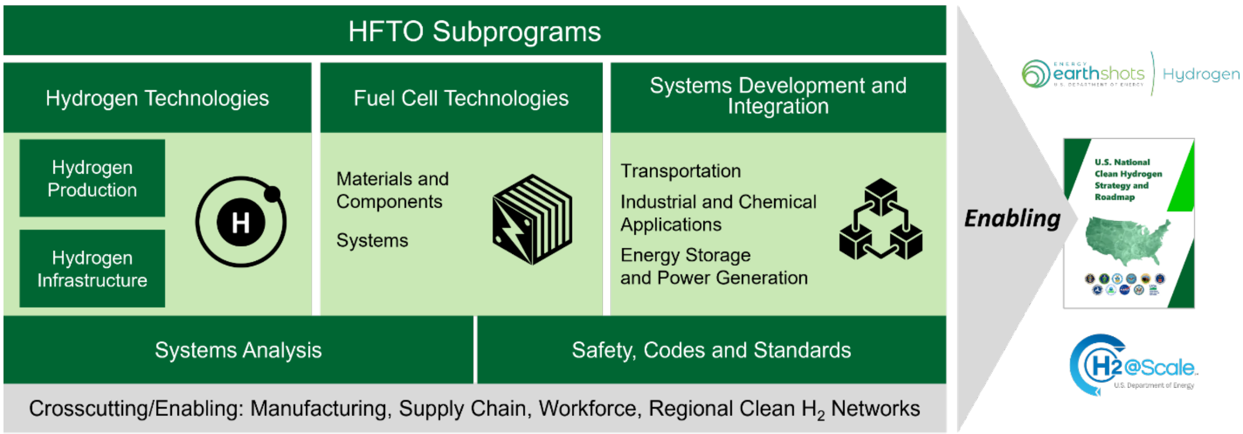

Figure 1.6. HFTO subprogram structure supporting national clean hydrogen priorities

HFTO has established the RD&D framework of subprograms illustrated in Figure 1.6 and described below:

- **Hydrogen Technologies** comprises two coordinated and closely related focus areas, both of which span materials-, component-, and system-level RD&D:
  - *Hydrogen Production* focuses on enabling affordable production of hydrogen from diverse renewable domestic resources.
  - *Hydrogen Infrastructure* focuses on enabling affordable and accessible delivery and storage infrastructure options.
- **Fuel Cell Technologies** focuses on the materials-, component-, and system-level RD&D for different fuel cell technologies and applications to enable highly efficient conversion of clean hydrogen for end uses such as transportation and backup-power generation using fuel cells.
- **Systems Development and Integration** focuses on the development and integration of complete hydrogen systems to enable first-of-a-kind demonstrations of integrated energy systems deploying clean hydrogen and fuel cell technologies in key hard-to-decarbonize sectors—including transportation, chemical and industrial processes, and energy storage and power generation.
- **Systems Analysis** encompasses crosscutting topics including data, modeling, and analysis that guides RD&D, and identifies priority markets for clean hydrogen technologies with impacts assessments.

- **Safety, Codes and Standards** encompasses crosscutting topics, including RD&D that informs safe design and operation of clean hydrogen technologies, while addressing regulatory and permitting challenges.

Overall cost reductions, including technology manufacturability and scale-up, are common crosscutting topics covered across the subprograms, as well as in collaboration with other DOE offices and federal agencies. Other crosscutting topics include workforce development; addressing DEIA; and ensuring well-paying U.S. jobs.

For each of these subprograms, the *MYPP* documents HFTO's plans for RD&D activities based on near-, mid-, and longer-term priorities:

- **Near- to mid-term priorities** are to enable cost reductions and demonstrate advances, including component and systems development and integration, leading to fully integrated systems.
- **Mid- to longer-term priorities** are early-stage materials and component research to enable innovation and leapfrog current approaches to meet ultimate targets.

HFTO has developed a multipronged, target-driven strategic approach to achieve its mission and support national priorities in clean hydrogen. This approach is illustrated in Figure 1.7, which shows specific priorities for each subprogram area—with darker shades indicating the time periods when a greater level of effort is planned. The subprogram priorities, along with supporting RD&D efforts, are described in detail in the corresponding subprogram chapters of the *MYPP*. Details for each of the subprograms are also summarized each year in the President's Congressional Budget Request, and HFTO uses annual appropriations to fund RD&D consistent with the overall strategy.

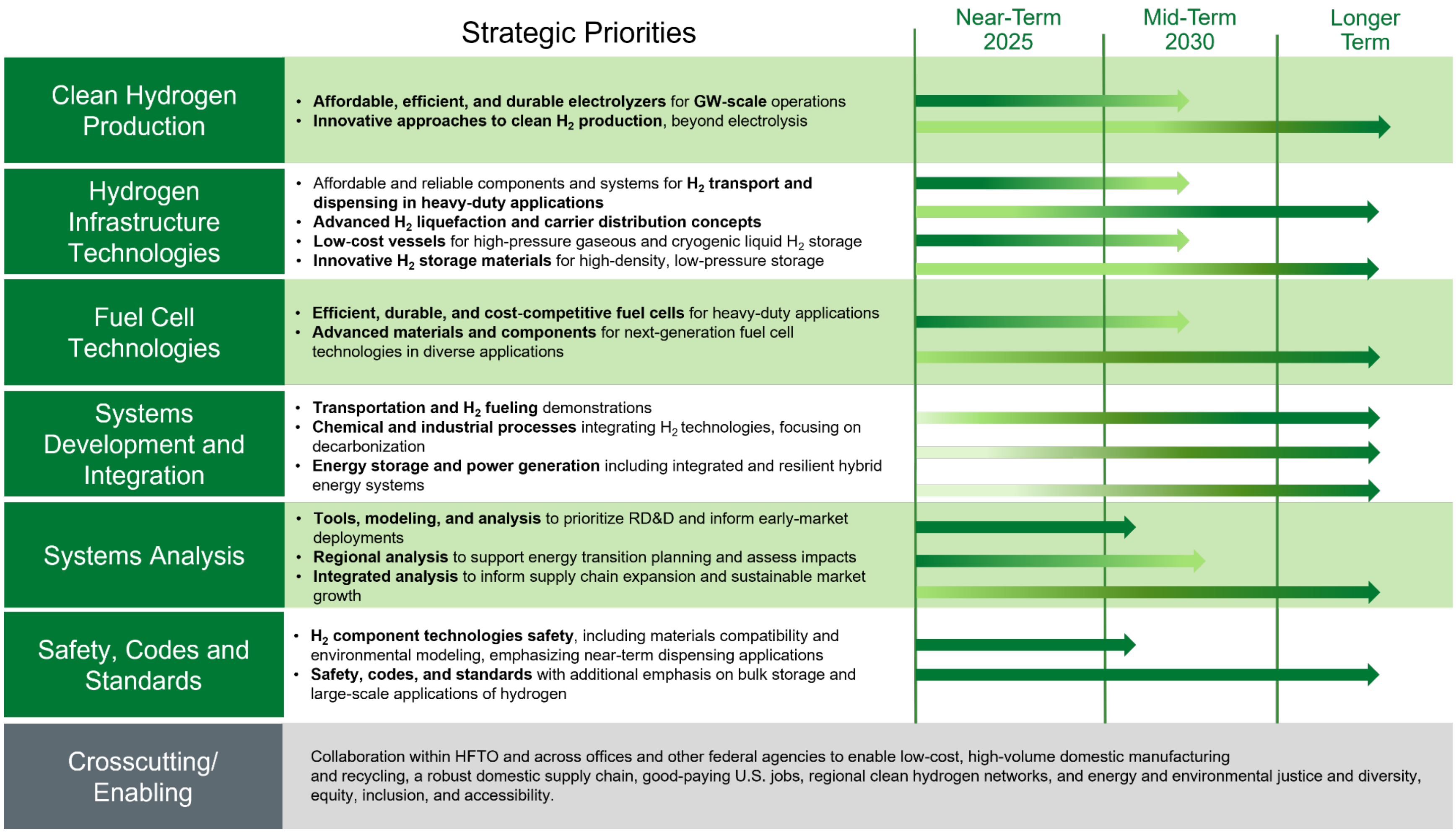

Figure 1.7. Strategic RD&D priorities in HFTO's portfolio, illustrating the multipronged approach—which includes near- to mid-term and longer-term priorities across most focus areas.

1.6 Target-Driven Approach

To effectively achieve outcomes aligned with its mission, HFTO defines and refines near- and longer-term goals with specific targets based on what is required for clean hydrogen and fuel cells to be cost-competitive across sectors. These targets are developed through techno-economic analysis and with extensive input from industry and other relevant stakeholders. Importantly, they are closely correlated with milestones in the *U.S. National Clean Hydrogen Strategy and Roadmap* shown in Table 1.1.

HFTO Key Target Examples

Targets are developed with stakeholder input to enable competitiveness with incumbent and emerging technologies. These targets guide the RD&D community and inform HFTO's portfolio of activities. Examples include the following.

Clean H_2 production:

- $2/kg by 2026; $1/kg by 2031

Electrolyzer systems (low temperature):

- 2026: $250/kW, 65% efficiency, 80,000-hour durability

Electrolyzer systems (high temperature):

- 2026: $500/kW, 76% efficiency, 40,000-hour durability

H_2 dispensed for heavy-duty transportation:

- 2028: <$7/kg

Fuel cell manufacturing for heavy-duty transportation:

- 2030: 20,000 stacks/year (single manufacturing system)

Fuel cell systems for heavy-duty transportation:

- 2030: $80/kW, 25,000-hour durability

The key priority underlying HFTO's targets is to achieve affordability at scale, in addition to improving—or at least not compromising—technological performance and reliability. Each of the subprograms addresses high-level cost targets through RD&D guided by detailed technical targets developed at the materials-, component-, and integrated systems level.

For each subprogram, the *MYPP* illustrates specific pathways HFTO has identified to achieve its targets—including detailed analysis of the key factors affecting targets in each technical area and how HFTO-funded efforts can address those factors. For example, Figure 1.8 shows at a high level the key drivers of fuel cell system cost (*donut* graphic on upper right), then shows a "waterfall" diagram that illustrates cost reductions that can be achieved across four different areas (manufacturing and scale, power density and platinum group metals [PGM], stack and balance of plant [BOP] components, and durability). The *MYPP* provides waterfall charts for additional technical topics such as electrolyzer capital cost, hydrogen storage system cost, and others.

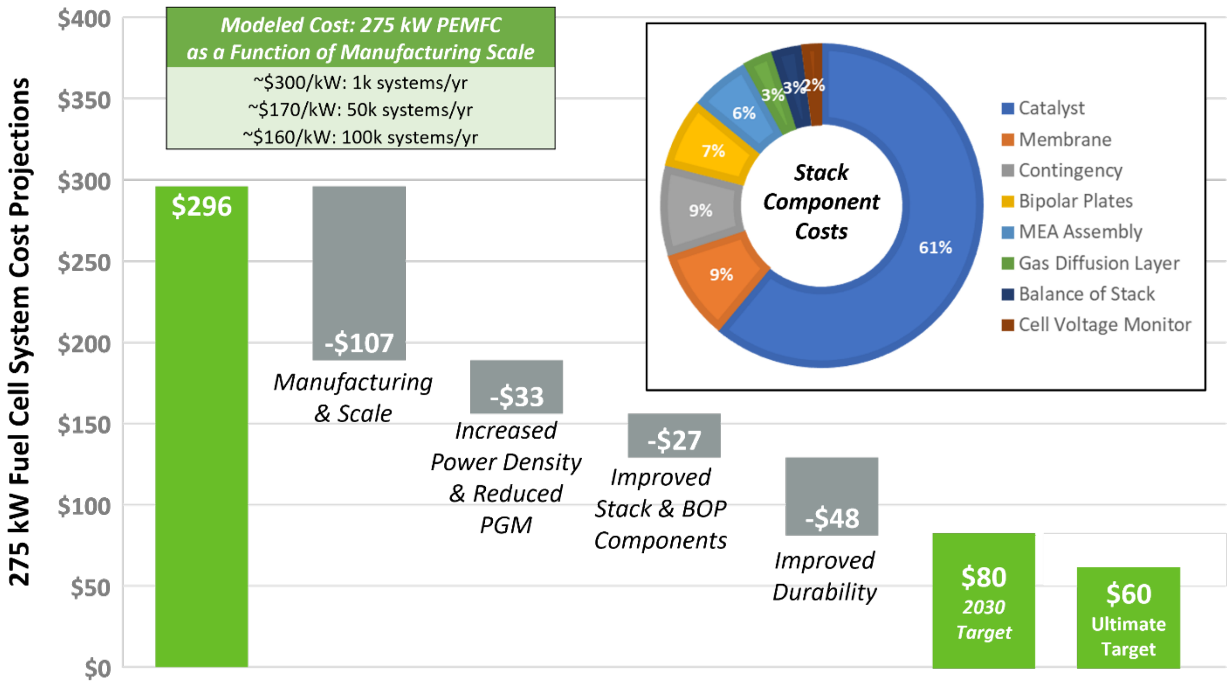

Figure 1.8. Example of "waterfall" chart showing pathways to meeting HFTO cost-reduction targets

Table 1.1 Examples of Key Milestones, Status and Targets

Includes key milestones adapted from the U.S. National Clean Hydrogen Strategy and Roadmap

	Examples of Key Milestones and Status (2023)	2024–2028	2029–2036
Production	• **Three first-of-a-kind demos** of electrolyzers with renewables and nuclear • **\$5 to \$7/kg** for clean H_2 from electrolysis • **~55 kWh/kg** efficiency, **~40,000-hour** (projected operation), ~\$1,500 to \$2,500 installed cost	• **Ten or more** demos with renewables, nuclear, and waste/fossil with CCUS • **\$2/kg clean H_2** from electrolysis at scale by 2026[a] • **51 kWh/kg** efficiency, **80,000-hour** life, and **\$250/kW** uninstalled cost for PEM electrolyzers	• **10 MMT** per year by 2030 or more of clean H_2 produced in the United States • **\$1/kg** clean H_2 production from diverse resources at scale[a] • **46 kWh/kg** efficiency; **80,000-hour** life; **\$100/kW** uninstalled cost for PEM electrolyzers
Infrastructure, Manufacturing, and Supply Chains	• **\$12 to 16/kg** H_2 (modeled cost including delivery and dispensing at fueling stations with electrolytic hydrogen)[b] • Initiated **four** carbon fiber R&D projects for cost reduction • Announced new awards to enable **10 GW electrolyzer manufacturing capacity** in the United States • Announced new awards to enable **14 GW fuel cell manufacturing capacity** in the United States • Announced **Recovery and Recycling Consortium** with industry, labs, and academia to address end-of-life for electrolyzers, fuel cells, and components	• **\$7/kg** H_2 cost at scale (modeled cost including production, delivery, and dispensing at fueling stations) • **50%** cost reduction of carbon fiber for H_2 storage vessels (vs. 2020) • **3 GW or more** electrolyzer manufacturing capacity (in operation) in the United States • **GW-scale** fuel cell and supply chain component manufacturing plants in operation in the United States • **>50%** of membrane/ionomer material recovery and **>95%** of PGMs recovery from fuel cell MEA from pathways identified through recycling and upcycling	• **\$4/kg** H_2 cost at scale (modeled cost including production, delivery, and dispensing at fueling stations) • Demonstrate carbon fiber cost reduction to meet \$9/kWh H_2 storage • **>10 GW/year** electrolyzer manufacturing capacity in operation in the United States to meet national targets • **>14 GW/year** fuel cell manufacturing capacity in operation in the United States to meet heavy-duty fuel cell demand (e.g., 15% of trucks) • **>70%** of membrane/ionomer material recovery and **99%** of PGMs from MEA pathways identified through recycling and upcycling
End Use	• **\$170/kW** heavy-duty truck fuel cell cost vs. \$200/kW baseline • Initiated **three SuperTruck projects** for medium- and heavy-duty trucks • Announced selection of **seven Regional Clean Hydrogen Hubs** (\$7 billion) • Announced funding opportunity for best practices on community benefit agreements	• **\$140/kW** heavy-duty truck fuel cell cost (modeled at 50,000 units/year manufacturing) • **Three** H_2 fuel cell Super Truck projects completed to demonstrate viability • **Four or more** Regional Clean Hydrogen Hubs using diverse resources and for multiple strategic end uses • **Four** template community benefit agreements	• **\$80/kW** heavy-duty truck fuel cell cost at high volumes while also meeting durability and performance • Follow-on truck and station demos in operation to meet market needs • **10 MMT** per year or more of clean H_2 used in strategic markets at scale aligned with the National Hydrogen Strategy goal

[a] Modeled cost at scale to meet Hydrogen Shot goal.

[b] Cost of \$7–\$11/kg for delivery and dispensing in early markets (based on modeled scenarios) and \$5/kg for clean H_2 production. Source: Bracci, Justin, Mariya Koleva, and Mark Chung. 2024. Levelized Cost of Dispensed Hydrogen for Heavy-Duty Vehicles. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5400-88818. https://www.nrel.gov/docs/fy24osti/88818.pdf.

CCUS: carbon capture, utilization, and storage; MEA: membrane electrode assembly; PEM: proton exchange membrane; PGM: platinum group metal

1.7 Impacts from Prior Investments

While Chapter 1.6 outlines aggressive targets for the future, it is important to recognize that HFTO has a proven track record of successfully driving down costs and addressing technical challenges through strategic deployment of RD&D funding. For example, HFTO-funded RD&D has resulted in reductions of over 90% in the adjusted uninstalled capital cost of proton exchange membrane (PEM) electrolyzers, as shown in Figure 1.9.[27] These cost reductions have been enabled by innovations developed through DOE-supported projects conducted in partnership with several manufacturers of PEM electrolyzers. The primary focus of this work has been on advances in PEM electrolyzer stacks—both in advancements to the underlying technology and in manufacturing innovations.

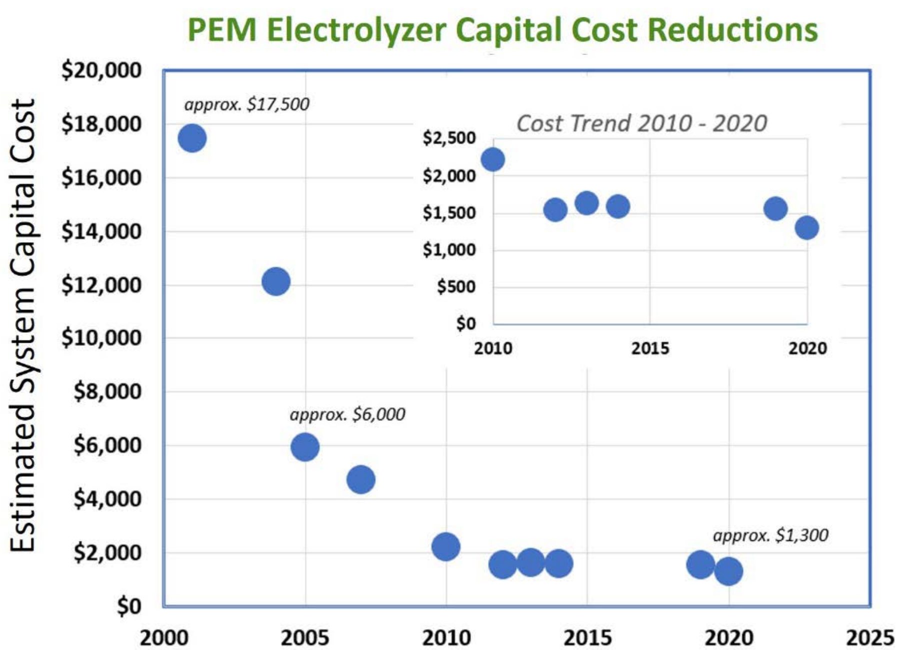

Figure 1.9. Historical reductions in the capital cost of PEM electrolyzers enabled by HFTO investments

The significant reductions in cost closely parallel HFTO funding for RD&D. Note that the data shown through 2020 represents the evolution and scale-up of relatively small electrolyzer systems (<1 MW); more recent advances in stack and system scale-up offer opportunities for further cost reduction, especially for larger multi-megawatt (MW) to gigawatt (GW) systems.

HFTO investments have had a similar impact on reducing costs for fuel cells used in transportation applications. Figure 1.10 shows the 70% reduction in fuel cell system cost for light

[27] Randolph, Katie, James Vickers, David Peterson, McKenzie Hubert, and Eric Miller. June 11, 2022. "Historical Cost Reduction of PEM Electrolyzers." DOE Hydrogen Program Record # 22002. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/22002-historical-cost-reduction-pem-electrolyzers.pdf?Status=Master. Note that the period from 2010 to 2018 (shown in the figure insert) shows only modest cost reductions, reflecting a period of limited/zero HFTO funding in electrolyzer RD&D.

duty vehicles from 2008 to 2020, achieved through RD&D focused on improvements in high-power performance along with reductions in platinum catalyst loading.[28]

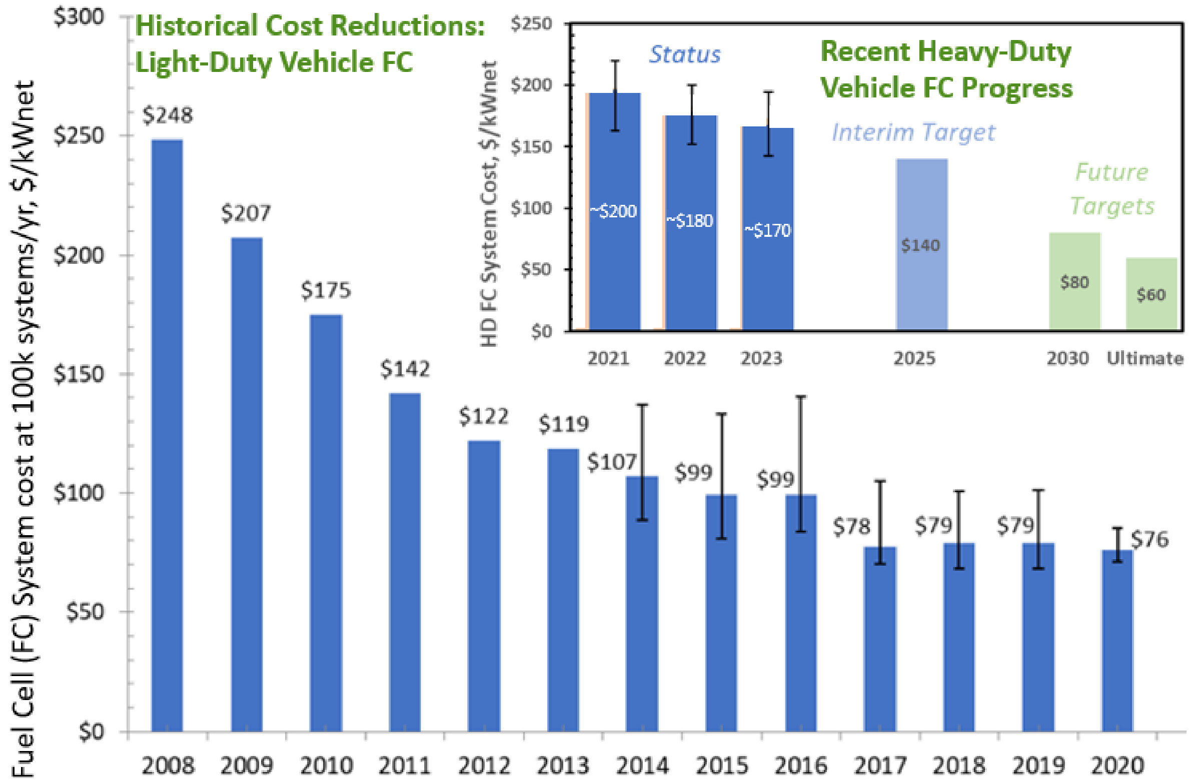

Figure 1.10. Historical reductions in fuel cell system costs enabled by HFTO investments

While past work focused on fuel cell cost reduction for light-duty vehicles, recent efforts prioritize fuel cell targets to meet the duty cycle, cost, and durability requirements for heavy- and medium-duty trucks. The Figure 1.10 inset includes the modeled fuel cell system cost status for heavy-duty vehicles based on recent analysis, compared with the interim target (2025) for a manufacturing volume of 50,000 systems per year, as well as a future 2030 target (for an $80/kW system) and ultimate target (for a $60/kW system) based on manufacturing volumes of 100,000 systems per year.

Complementing the milestones in Table 1.1, additional examples of recent accomplishments enabled by HFTO funding include:[29]

[28] Kleen, Gregory, and Elliot Padgett. January 7, 2021. "Durability-Adjusted Fuel Cell System Cost." DOE Hydrogen Program Record # 21001. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/21001-durability-adjusted-fcs-cost.pdf. The uncertainty bars in the charts reflect system costs with 90% confidence based on a Monte Carlo distribution.

[29] Office of Energy Efficiency and Renewable Energy. July 2023. "Progress in Hydrogen and Fuel Cells." DOE/EE-2743. https://www.energy.gov/eere/fuelcells/articles/progress-hydrogen-and-fuel-cells.

- Improved the performance of specific PGM-free catalysts for fuel cells by approximately 60% over the 2021 baseline.
- Achieved over 10,000 hours of high-temperature electrolyzer testing.
- Demonstrated 1.25 MW electrolysis integrated with nuclear power for H_2 production.
- Commissioned a first-of-a-kind test facility for high-throughput hydrogen fueling; and demonstrating a 10 kg/min average H_2 fueling rate for heavy-duty applications.
- Demonstrated greater than 1.5 MW of H_2 fuel cells for data center resilience.
- Reduced the cost of advanced onboard compressed-hydrogen storage systems by 30% since 2013.
- Achieved a 40% footprint reduction in liquid H_2 fueling stations vs. current code (2016).
- Achieved a 50% increase in seal and metal durability in H_2 service vs. the 2018 baseline.
- Demonstrated H_2 flow meters with 5% or better accuracy for flows up to 20 kg/min.
- Developed an American Society of Mechanical Engineers Code Case that extends H_2 storage vessels design life by up to 300%.
- Demonstrated 1 ton/week iron reduction with H_2, with a pathway to 5,000 ton/day.
- Demonstrated fuel cell delivery trucks in a disadvantaged community.

HFTO RD&D has achieved many prior year goals and targets; many of these successes are tracked in the Hydrogen Program Records.[30] Additional detailed examples of historical progress to date are included in individual subprogram chapters of this document.

1.8 *MYPP* Structure

The *MYPP* outlines remaining technical challenges that must be systematically addressed through further targeted RD&D funding to ensure continued progress toward national clean hydrogen goals. Chapter 2 provides an explanation of HFTO program implementation, with the remainder of the document providing a detailed description of HFTO's comprehensive portfolio of RD&D and enabling activities, organized by chapters focused on each of the subprograms. Each chapter includes specific technology focus areas in the subprograms' near- and longer-term strategic approach, highlighting specific challenges, risk mitigation strategies, and examples of relevant techno-economic targets and milestones. Additional references and links to important supplemental information are provided, including technology-specific target listings and status updates.

[30] U.S. Department of Energy. "Hydrogen Program: Program Records." https://www.hydrogen.energy.gov/library/program-records.

2 Program Implementation

2.1 Overview

HFTO implements programmatic activities in support of nationally established priorities for clean energy and environmental justice, such as those articulated in the ***U.S. National Clean Hydrogen Strategy and Roadmap***.[31] HFTO program implementation comprises of RD&D activities managed across its subprograms as well as stakeholder engagement and collaborative activities with diverse government, community, industry, academic, and national laboratory stakeholders. HFTO adheres to the guiding principles illustrated in Figure 2.1 established for all federal agencies, with a specific focus on RD&D and enabling activities in the production, transport, delivery, storage, and end-use of clean hydrogen. Program implementation stemming from specific congressional authorizations, and adhering to these guiding principles, is described below.

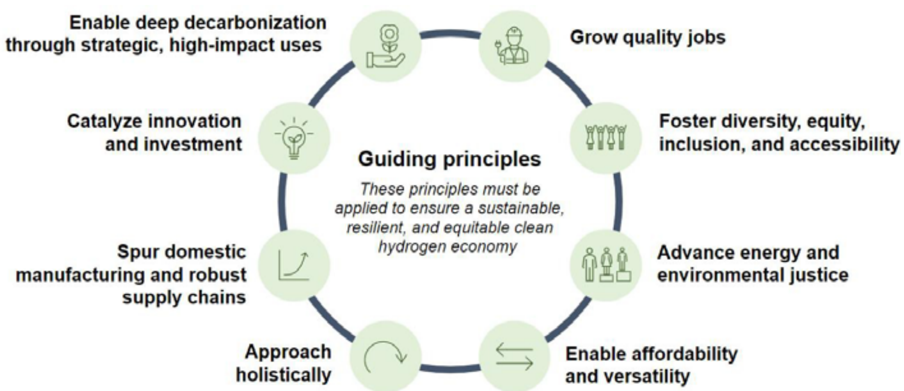

Figure 2.1. Eight guiding principles for the development of clean hydrogen production, transport, delivery, storage, and use

2.2 Congressional Authorization

Various statutory authorities have enabled DOE to establish a robust RD&D program in hydrogen and fuel cells technologies, including: the Spark M. Matsunaga Hydrogen Research, Development, and Demonstration Act of 1990; the Energy Policy Act of 2005; the Energy Independence and Security Act of 2007; and U.S. Code (42 U.S. Code § 16154). These authorizing statutes, policies, and annual appropriations provide the basis for much of the work discussed in the *MYPP*. In 2021, the Infrastructure Investment and Jobs Act (Public Law 117-58), also known as the Bipartisan Infrastructure Law (BIL) was signed into law, authorizing funds for clean hydrogen RD&D and providing specific amendments to the Energy Policy Act of 2005. In 2022, the

[31] U.S. Department of Energy. *U.S. National Clean Hydrogen Strategy and Roadmap*. 2023. https://www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap.

Inflation Reduction Act was signed into law (Public Law 117-169), providing additional policies and incentives for hydrogen including a production tax credit to further boost a U.S. market for clean hydrogen.

2.3 Program Management

Stakeholder Input

To maintain alignment with the priorities of key stakeholders—including industry, end users, academia, the investment community, and other government agencies—HFTO actively solicits input to inform its programmatic activities across its subprograms. Among the primary channels for this input are requests for information and workshops conducted by DOE to help establish high-level program direction and to develop and update technology-specific RD&D plans. These workshops convene a wide range of stakeholders and provide an open forum for discussion of the status of the technologies and the challenges facing their development and deployment. Results from these stakeholder input activities feed into the development of HFTO strategies and funding plans, including in developing rigorous targets and milestones for all RD&D pathways.

Funding Mechanisms

HFTO's activities are funded using various competitive mechanisms, including funding opportunity announcements (FOAs), through which industry, university, national laboratory, and other private-sector projects are selected. HFTO also issues separate lab calls to make selections for national laboratory projects; uses cooperative research and development agreements (CRADAs) to encourage partnerships between the private sector and national labs for joint development; and creates strategic partnership projects, through which industry can contract company-specific tasks to be conducted at national labs.

Project Management

HFTO's comprehensive RD&D portfolio comprises projects that are competitively selected under the various funding mechanisms. A rigorous selection process ensures projects are selected based on technical feasibility, high-impact potential, innovation, and the likelihood of making progress toward HFTO technical targets. Each project proposal is reviewed by independent experts. The proposals are evaluated based on a specific set of criteria and how well the proposal helps the HFTO to address the challenges, targets, and goals. A federal panel considers the independent experts' review comments when selecting projects for award negotiations.

Once a project is selected, funding award recipients submit a plan detailing their approach to reaching project objectives and overcoming technical challenges. Each project plan incorporates go/no-go decisions to help project managers decide whether the project should continue into the next budget period. These go/no-go decisions define performance-based milestones and quantitative metrics at the subprogram, task area, and project level.

HFTO regularly assesses progress, approaches, and priorities by monitoring portfolio performance. An Annual Merit Review and Peer Evaluation of the DOE Hydrogen Program portfolio and HFTO projects allows external experts to evaluate project objectives, approach, success, and relevance. These performance assessment activities provide avenues for input from other government agencies, industry representatives, academia, other stakeholders, and independent subject matter experts on program effectiveness and progress toward the Hydrogen Program's mission and goals.

2.4 RD&D Consortium Model

Activities across government, industry, and academia are working in concert with HFTO to advance the clean hydrogen and fuel cell technologies described in the *MYPP*. As a key enabler of such collaboration, HFTO has pioneered a consortium model comprising national laboratory core teams that make available their world-class resources and expertise to universities and industry through consultations as well as collaborative projects awarded through FOAs and CRADAs, as illustrated in Figure 2.2. Each consortium has a specific technical focus area, with comprehensive RD&D efforts within the core lab team and with the collaborative projects.

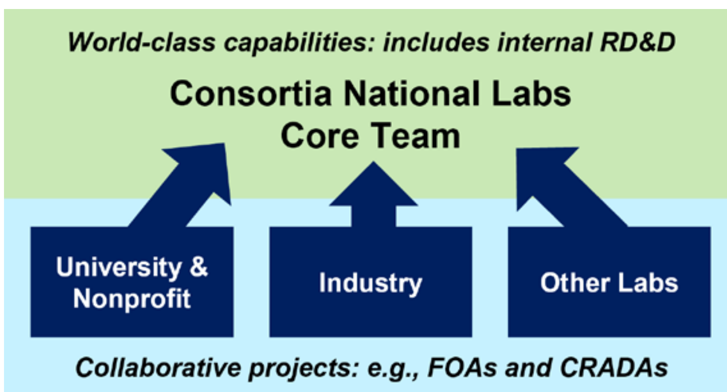

Figure 2.2. HFTO consortia model approach to research collaborations

HFTO Consortia Advancing RD&D in Hydrogen and Fuel Cell Technologies

Million Mile Fuel Cell Truck (M2FCT) focuses on RD&D to improve fuel cell durability, performance, and cost to better position fuel cells as a viable option in the long-haul trucking market and other heavy-duty applications: M2FCT Consortium

Hydrogen from Next-generation Electrolyzers of Water (H2NEW) conducts RD&D to achieve large-scale, affordable electrolysis powered by clean electricity, supporting large industry deployment by enabling more durable, efficient, and low-cost electrolyzers: H2NEW Consortium

HyBlend addresses technical barriers to blending hydrogen in natural gas pipelines through materials compatibility RD&D and analysis that informs development of publicly accessible assessment tools on blending: HyBlend Consortium

Hydrogen Materials Compatibility Consortium (H-Mat) focuses on crosscutting R&D on hydrogen materials compatibility to improve the reliability and reduce the costs of materials, and to inform relevant codes and standards: H-Mat Consortium

Hydrogen Materials Advanced Research Consortium (HyMARC) addresses unsolved scientific challenges in the development of viable solid-state materials for onboard storage of H_2 that could lead to more reliable and economic hydrogen fuel cell vehicles: HyMARC Consortium

HydroGEN Advanced Water Splitting Materials (HydroGEN) focuses on innovative R&D on advanced water-splitting materials, primarily for photoelectrochemical, solar thermochemical, and advanced electrolytic hydrogen production pathways: HydroGEN Consortium

Electrocatalysis Consortium (ElectroCat) focuses on accelerating the R&D of catalysts made without platinum group metals (PGM-free) for use in fuel cells and electrolyzers: ElectroCat Consortium

Roll-to-Roll Consortium (R2R) focuses on membrane electrode assembly manufacturing technology advancements to reduce costs for fuel cells and electrolyzers.

2.5 Collaboration Networks

In addition to its internal collaborative RD&D, HFTO engages in coordinated activities with diverse stakeholders involved in the development of clean hydrogen and fuel cell technologies, including other DOE offices; federal, state, and local government agencies; public-private partnerships with industry; and international partnerships. The aim of such broader collaboration is to optimize federal investments, best leverage available resources, avoid duplication, and ensure consistent messaging to stakeholders.

DOE Collaboration

While HFTO has had the lead role in coordinating hydrogen-related activities across the government for over two decades, multiple DOE offices are engaged either directly or indirectly in hydrogen-related activities, including offices under the Under Secretary for Science and Innovation like EERE, FECM, NE, OE, and SC; offices under the Under Secretary for Infrastructure like LPO, MESC, and OCED; and Secretary-level offices like ARPA-E.[32] These offices are core to the DOE Hydrogen Program, whose structure is illustrated in Figure 2.3; they collaborate regularly to evaluate technical progress, share programmatic developments, share best practices on technical management, and assess the impacts of alternative technology pathways from environmental, energy, equity, and economic standpoints.

[32] EERE: Office of Energy Efficiency and Renewable Energy; FECM: Office of Fossil Energy and Carbon Management; NE: Office of Nuclear Energy; OE: Office of Electricity; SC: Office of Science; LPO: Loan Programs Office; MESC: Office of Manufacturing and Energy Supply Chains; OCED: Office of Clean Energy Demonstrations; ARPA-E: Advanced Research Projects Agency-Energy; AE: Arctic Energy Office; EJE: Office of Energy Justice and Equity; IA: Office of International Affairs; IE: Office of Indian Energy Policy and Programs; OTT: Office of Technology Transitions.

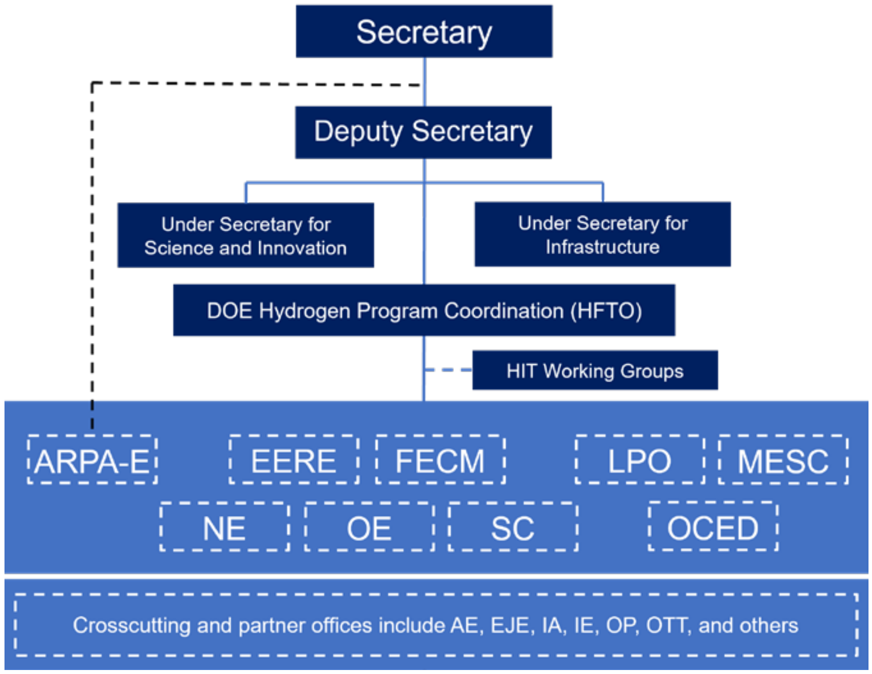

Figure 2.3. DOE Hydrogen Program organizational structure

HFTO also had a lead role in supporting the launch of the Office of Clean Energy Demonstrations (OCED) and the Regional Clean Hydrogen Hubs and continues to support OCED in execution of the $7 billion announced for seven regional clean hydrogen hubs. The *DOE Hydrogen Program Plan*[33] catalogs coordinated clean hydrogen and fuel cell activities across the DOE offices, spanning fundamental scientific research and development; applied research, development, and demonstration; and scale-up and deployment activities. The collaborative cycle of research, development, demonstration, and deployment (RDD&D) adopted by the DOE Hydrogen Program is illustrated in Figure 2.4, aimed at accelerating the technology-, manufacturing-, and commercial-readiness of affordable options for clean hydrogen production, storage, delivery, and utilization across sectors.

[33] U.S. Department of Energy. *Department of Energy Hydrogen Program Plan.* November 2020. DOE/EE-2128. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/hydrogen-program-plan-2020.pdf.

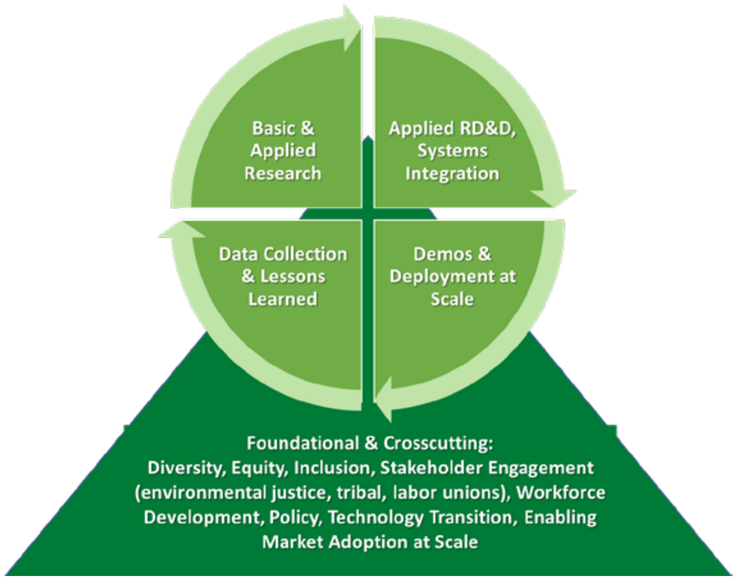

Figure 2.4. DOE's foundational and crosscutting efforts support the entire life cycle, from basic research through large-scale deployment.

DOE established the Hydrogen Joint Strategy Team (JST) with representatives from offices across the department to better coordinate the spectrum of RDD&D efforts in targeted focus areas of the *Hydrogen Program Plan*, as shown in Figure 2.5.

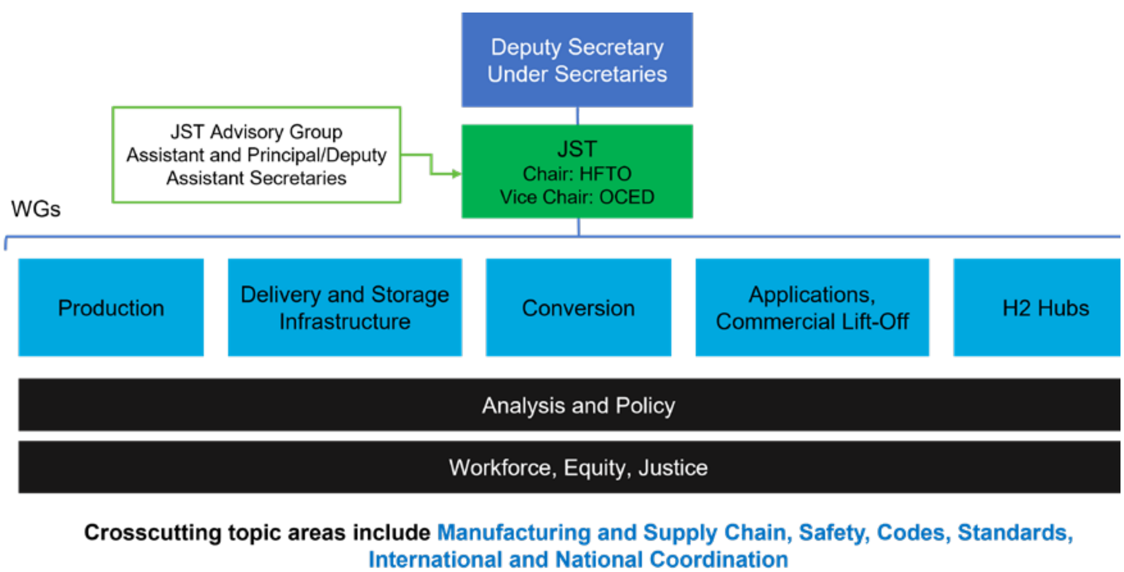

Figure 2.5. DOE Hydrogen Joint Strategy Team framework and focus areas

In addition to coordinating within DOE on the Hydrogen Program, HFTO partners with EERE offices to address decarbonization across many sectors. For example, HFTO collaborates with

EERE Sustainable Transportation pillar offices in several key areas including: sustainable aviation fuels and biobased hydrogen production with the Bioenergy Technologies Office, hydrogen internal combustion engines and the SuperTruck program with the Vehicle Technologies Office, and infrastructure and fueling corridors with the Joint Office of Energy and Transportation. In addition, modal leads across the offices coordinate on technologies for both road and offroad vehicles, rail, marine, and aviation sectors. Within the renewable energy pillar of EERE, HFTO collaborates on relevant topics such as solar thermochemical (STCH) hydrogen production and electrolysis via both onshore and offshore wind. And within EERE's buildings and industry pillar, HFTO collaborates on multiple topics including hydrogen for steel manufacturing, advanced manufacturing technologies such as carbon fiber and roll-to-roll processes, and fuel cells for buildings.

Domestic Coordination

In addition to coordinating hydrogen and fuel cells RD&D within DOE as described in the *DOE Hydrogen Program Plan*, HFTO has been leading the Hydrogen and Fuel Cell Interagency Working Group since 2005, which has provided a forum for sharing research results, technical expertise, and lessons learned about hydrogen program implementation and technology deployment, as well as coordinating related projects across federal agencies. Recently, partner agencies have elevated the Interagency Working Group to the deputy secretary level across over 10 agencies to collaborate through the HIT to accelerate progress in hydrogen technologies. The HIT builds upon the Interagency Working Group, which DOE established in response to the Energy Policy Act of 2005, which required the Secretary of Energy to coordinate across agencies on hydrogen.[34] To facilitate coordination, the HIT is structured into working groups and crosscutting teams focused on addressing a portfolio of key clean hydrogen and fuel cell priorities, as illustrated in Figure 2.6. This structure is complementary to the DOE Hydrogen Joint Strategy Team framework shown in Figure 2.5.

[34] Energy Policy Act. 42 USC 16155 (Pub. L. 109–58, title VIII, §806, Aug. 8, 2005, 119 Stat. 848).

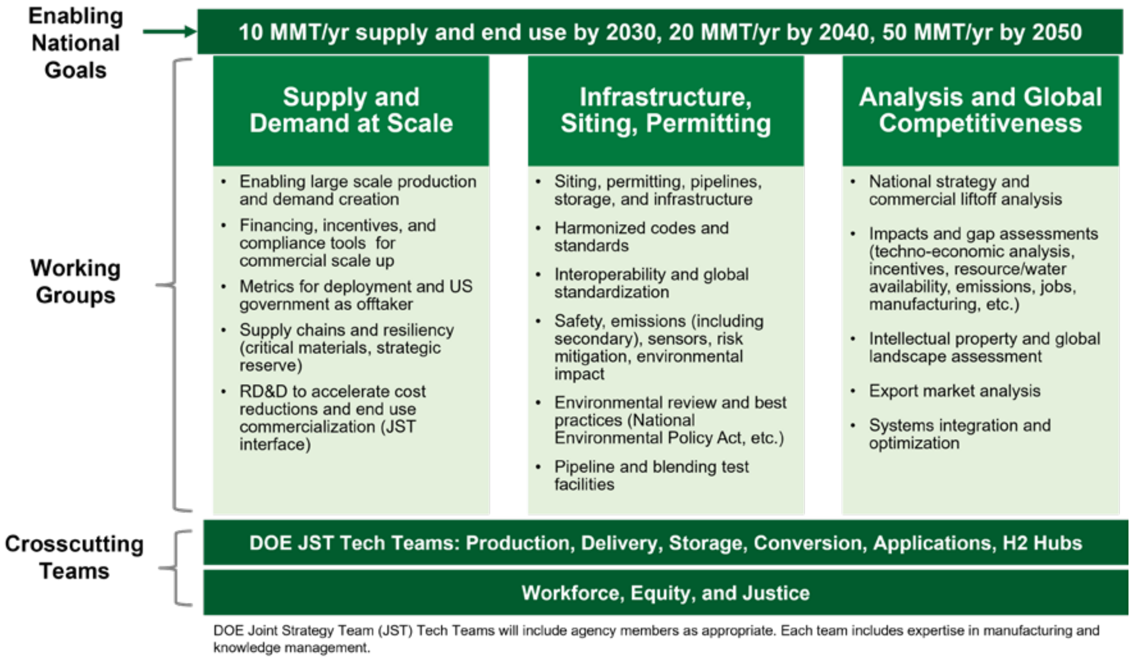

Figure 2.6. HIT working group structure and focus areas

In addition to this federal coordination, HFTO engages with several state governments and with private-sector and nonprofit stakeholders through partnerships to ensure that the RD&D efforts of government, academia, and industry are well coordinated, their diverse capabilities are well integrated, and their resources are effectively utilized. Examples of successful partnerships have included U.S. DRIVE,[35] the 21st Century Truck Partnership,[36] and the H2@Scale project consortium.[37]

International Coordination

HFTO engages in multiple international activities and partnerships to share technology lessons learned, foster collaboration, and advance mutual RD&D areas of interest at a global scale. Key examples include the Clean Energy and Hydrogen Energy Ministerials, the International Energy Agency, the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), Mission Innovation, and various bilateral and multilateral arrangements with countries involved in hydrogen and fuel cell activities. The Breakthrough Agenda[38] was established in 2021 at COP26 in Glasgow as a coordination framework to help unify various organizations and initiatives and avoid duplication, leverage resources, and accelerate the successful scale-up of clean hydrogen

[35] Vehicle Technologies Office. "U.S. DRIVE." https://www.energy.gov/eere/vehicles/us-drive.
[36] Vehicle Technologies Office. "21st Century Truck Partnership." https://www.energy.gov/eere/vehicles/21st-century-truck-partnership.
[37] Hydrogen and Fuel Cell Technologies Office. "H2@Scale." https://www.energy.gov/eere/fuelcells/h2scale.
[38] "The Breakthrough Agenda." https://breakthroughagenda.org/.

technologies. HFTO serves as a colead, along with counterparts in the United Kingdom and India, to coordinate across international hydrogen initiatives through the Breakthrough Agenda.

2.6 Crosscutting Priorities

To achieve national clean energy goals through the advancement of clean hydrogen and fuel cell technologies, HFTO's RD&D portfolio and collaborative activities support important crosscutting priorities in diversity, equity, inclusion, and accessibility (DEIA); energy and environmental justice; workforce development; and innovations in manufacturing and supply chain development.

Diversity, Equity, Inclusion, and Accessibility and Justice40

Aligned with DOE priorities, HFTO promotes DEIA, including through stewardship and promotion of diverse and inclusive workplaces that value and celebrate a diversity of people, ideas, cultures, and educational backgrounds that are foundational to delivering on the goals in the *MYPP*. HFTO is also committed to ensuring that its technologies contribute substantively to the holistic approach of the DOE Hydrogen Program, which includes addressing energy and environmental justice and equity in support of national priorities in the Justice40 Initiative.[39]

HFTO takes several approaches to ensure DEIA and environmental justice principles are present in all aspects of program implementation, supported by modeling and analysis to understand and quantify environmental and economic effects of hydrogen and fuel cell technologies. Important activities include:

- **Community engagement*:*** HFTO demonstrates commitment to DEIA and environmental and energy justice through community engagement. Activities include listening to and increasing transparency with various impacted groups such as tribes and community members who live in disadvantaged communities.
- **Prioritizing safety and positive impacts of hydrogen technologies:** HFTO prioritizes safety and positive impacts of hydrogen technology for all. The crosscutting Safety Codes and Standards subprogram ensures that safety is paramount in all HFTO-funded activities.

Figure 2.7 illustrates the important intersection of DEIA and justice with community engagements and job creation, specifically highlighting HFTO's priorities in equity as well as energy and environmental justice.

[39] The White House. "Justice40: A Whole-of-Government Initiative." https://www.whitehouse.gov/environmentaljustice/justice40/.

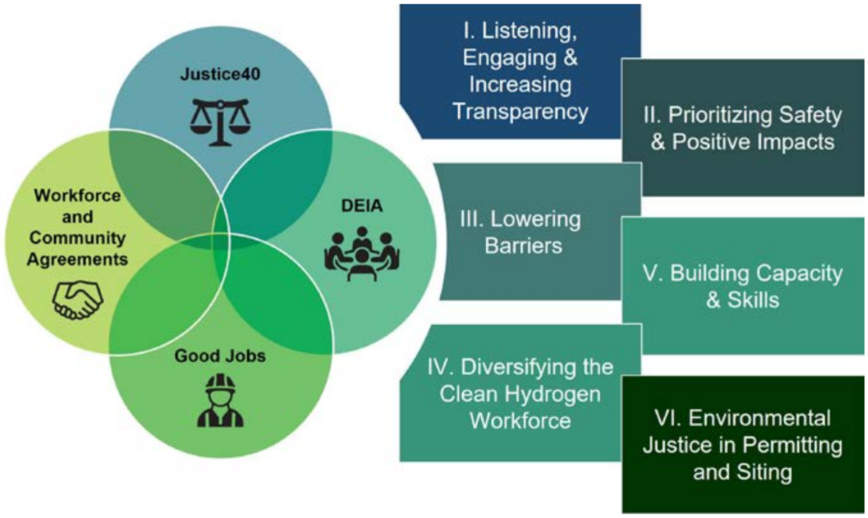

Figure 2.7. HFTO's holistic approach, prioritizing diversity, equity, environmental justice, and jobs creation, leveraging strong community engagement

HFTO continues to advance DEIA by lowering barriers to funding and designing new tools and opportunities to facilitate partnerships that will broaden access to DOE funding. Activities related to decreasing barriers include offering prizes that require less effort to apply and encourage more first-time applicants. Additionally, the office has designed and released funding opportunities specifically for minority-serving institutions and historically Black colleges and universities. HFTO continuously broadens its pool of participants by funding nontraditional, emerging, and historically underfunded investigators through such programs as the Minority Educational Institution Student Partnership Program. In addition to domestic efforts, HFTO spearheaded the launch of H2–DEIA[40] as a global platform to advance DEIA and share best practices, through IPHE and with the Hydrogen Council, a global industry partnership.

Workforce Development

A knowledgeable and well-trained workforce is essential for meeting future energy demands, and a growing hydrogen and fuel cells industry has the potential to create opportunities for individuals with a wide range of skills and training. DOE's *Pathways to Commercial Liftoff: Clean Hydrogen* report[41] estimated that approximately 100,000 new direct and indirect jobs could be created related to the build-out of new projects and clean hydrogen infrastructure. Direct jobs relate to roles such as engineering and construction, and indirect jobs relate to manufacturing and the raw material supply chain. HFTO is advancing American energy security and economic development

[40] H2–DEIA. https://h2-deia.org/.
[41] U.S. Department of Energy. *Pathways to Commercial Liftoff: Clean Hydrogen*. March 2023. https://liftoff.energy.gov/clean-hydrogen/.

through the development of tools and information on the careers, education, and training opportunities available to meet the needs of a growing hydrogen and fuel cells workforce.

In support of both DEIA and workforce development priorities, HFTO is also committed to diversifying the hydrogen workforce both within the office and externally. Workforce DEIA activities include engaging with diverse audiences through STEM initiatives, prioritizing outreach efforts to reach nontraditional audiences, and providing support for faculty and students at minority-serving institutions to expand their research capacities in clean hydrogen. An example is the expansion of the H_2EDGE initiative,[42] Figure 2.8, which was designed to engage historically Black colleges and universities. With DOE support, EPRI, GTI Energy, and partner universities have created the H_2EDGE initiative (Hydrogen Education for a Decarbonized Global Economy) to develop and train a workforce for the emerging hydrogen technology industry and its end-use applications.

Figure 2.8. The H_2EDGE initiative is advancing the emerging hydrogen workforce by developing newly trained personnel and enabling the existing workforce to migrate into the hydrogen field.

Manufacturing and Supply Chain Innovations

For hydrogen to transition from niche applications to mass markets, it will be essential to develop industrial-scale techniques, processes, and facilities for manufacturing hydrogen-related technology components and systems at large volumes. A robust domestic supply chain will be needed to ensure the United States stays at the forefront of this emerging global industry. While the bulk of the investment needed to build manufacturing capacity will fall to industry—as incentivized by growing market demands—RD&D efforts will be needed to overcome technical challenges and accelerate progress.

[42] Electric Power Research Institute. "H_2EDGE: Summary of the Project." https://grided.epri.com/H2EDGE.html.

By developing processes and technologies specifically tailored to high-volume manufacturing, RD&D efforts can help achieve economies of scale in manufacturing. These efforts can also lead to additional technology and systems-integration improvements, resulting in even greater cost reductions. Key opportunities for crosscutting advances include development of:

- High-speed manufacturing techniques for processes such as forming, stamping, molding, sealing, joining, coating, and roll-to-roll processing.
- Best practices for material and component handling.
- Additive and automated manufacturing/assembly processes.
- Technologies for in-line diagnostics and quality control/quality assurance.
- Sensors and other technologies to reduce manufacturing defects in high-throughput production.
- Manufacturing processes and technology designs that enable efficient recycling/upcycling, especially of critical materials.

Standardized designs for systems and components are also needed to unify specifications among system and component providers, which simplifies technology development, lowers supplier costs, and can lead to more robust supply chains. HFTO coordinates closely with DOE's Manufacturing and Energy Supply Chains office as well as the Office of Policy on tax credits and other initiatives to accelerate domestic manufacturing and global competitiveness.

2.7 Conclusion

Crosscutting activities within HFTO include RD&D aimed at addressing manufacturing and supply chain challenges as well as associated Justice40 and workforce development benefits. To achieve national clean energy goals through the advancement of clean hydrogen and fuel cell technologies, HFTO supports important crosscutting priorities in DEIA; energy and environmental justice; safety; workforce development; and innovations in manufacturing and supply chain development.